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Applied Thermodynamics

Gas Power Cycles

By:
Mohd Yusof Taib
Faculty of Mechanical Engineering
myusof@ump.edu.my

Chapter Description

- Aims
  - To identify and recognized ideal thermodynamics cycle.
  - To analyze working principle of basic thermodynamics cycle and system.

- Expected Outcomes
  - Able to analyze performance of gas power in actual application of engineering.
  - Able to analyze gas power cycle using variation and constant specific heat.

- References
  - Yunus A. Cengel Michael A.Boles. “Thermodynamics: An Engineering Approach”, 8 Edition, McGraw-Hill Education, (2014).
  - Michael J. Moran, Howard N. Shapiro, Daisie D. Boettner, Margaret B. Bailey. “Fundamentals of Engineering Thermodynamics”, 8th Edition, Wiley, (2014).

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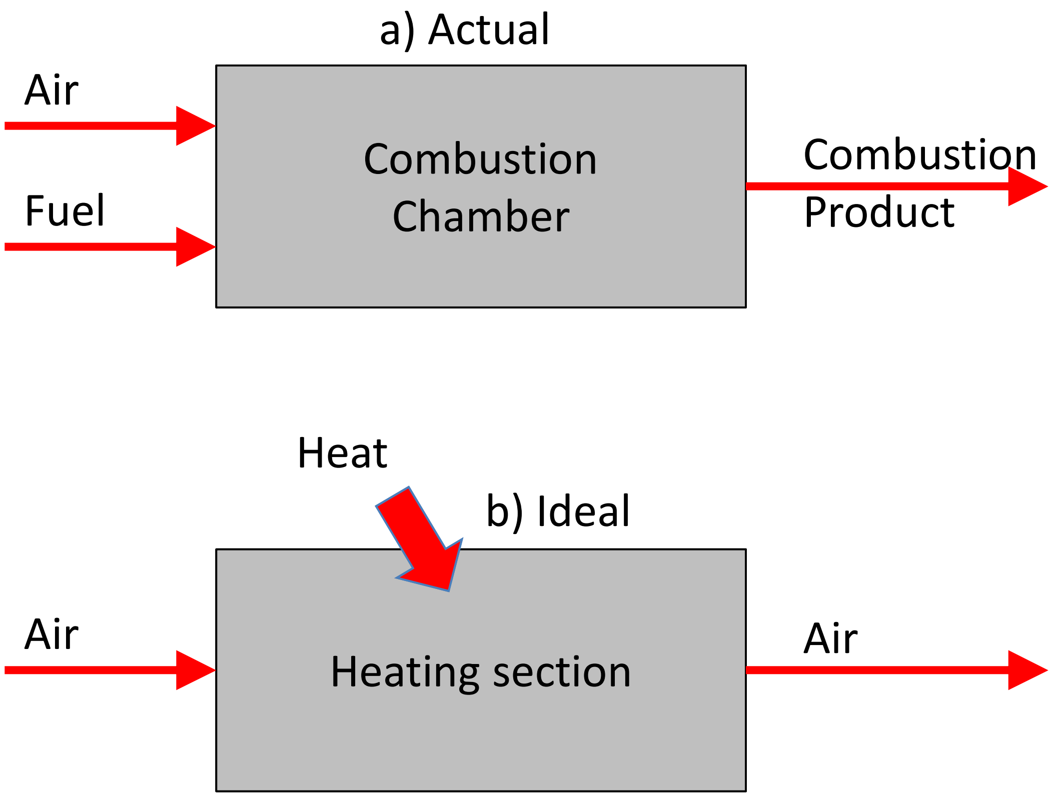
Air Standard Assumption



a) Actual

Air

Fuel

Combustion Chamber

Combustion Product

Heat

b) Ideal

Air

Heating section

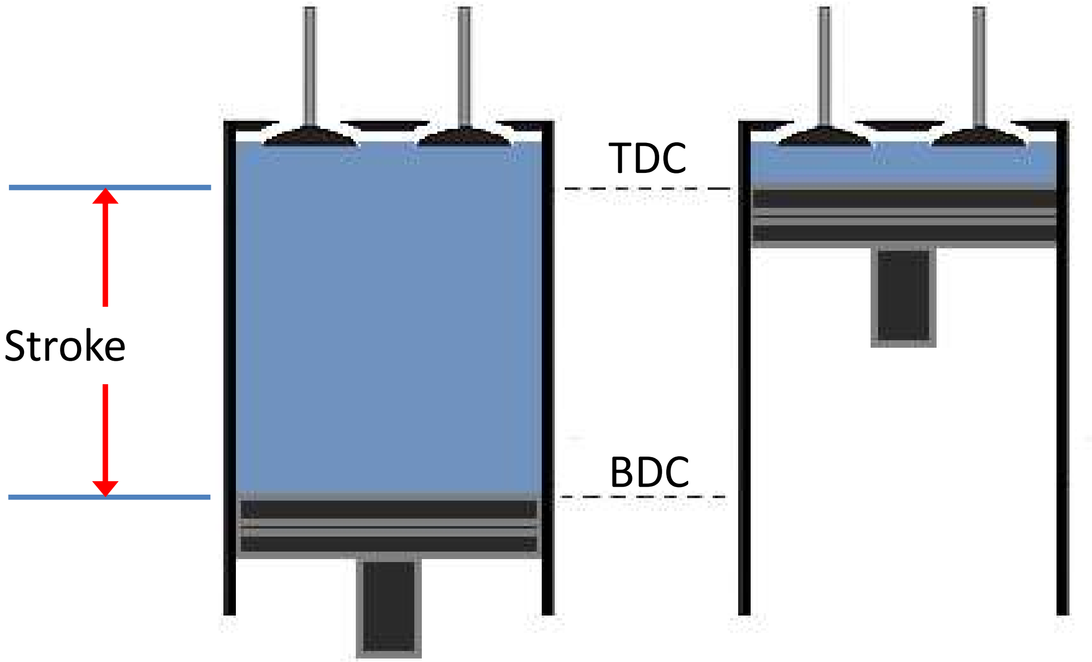
Air

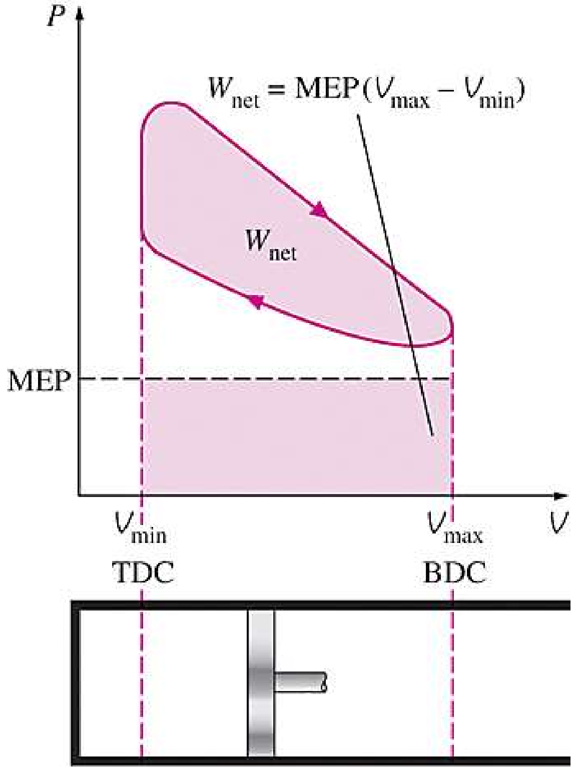
Assumptions:

1. The working fluid is air, which continuously circulates in a closed loop and always behaves as an ideal gas.
2. All the processes that make up the cycle are internally reversible.
3. The combustion process is replaced by a heat-addition process from an external source.
4. The exhaust process is replaced by a heat-rejection process that restores the working fluid to its initial state.

AN OVERVIEW OF RECIPROCATING ENGINES

- **Spark-ignition (SI) engines**
- **Compression-ignition (CI) engines**





Compression ratio

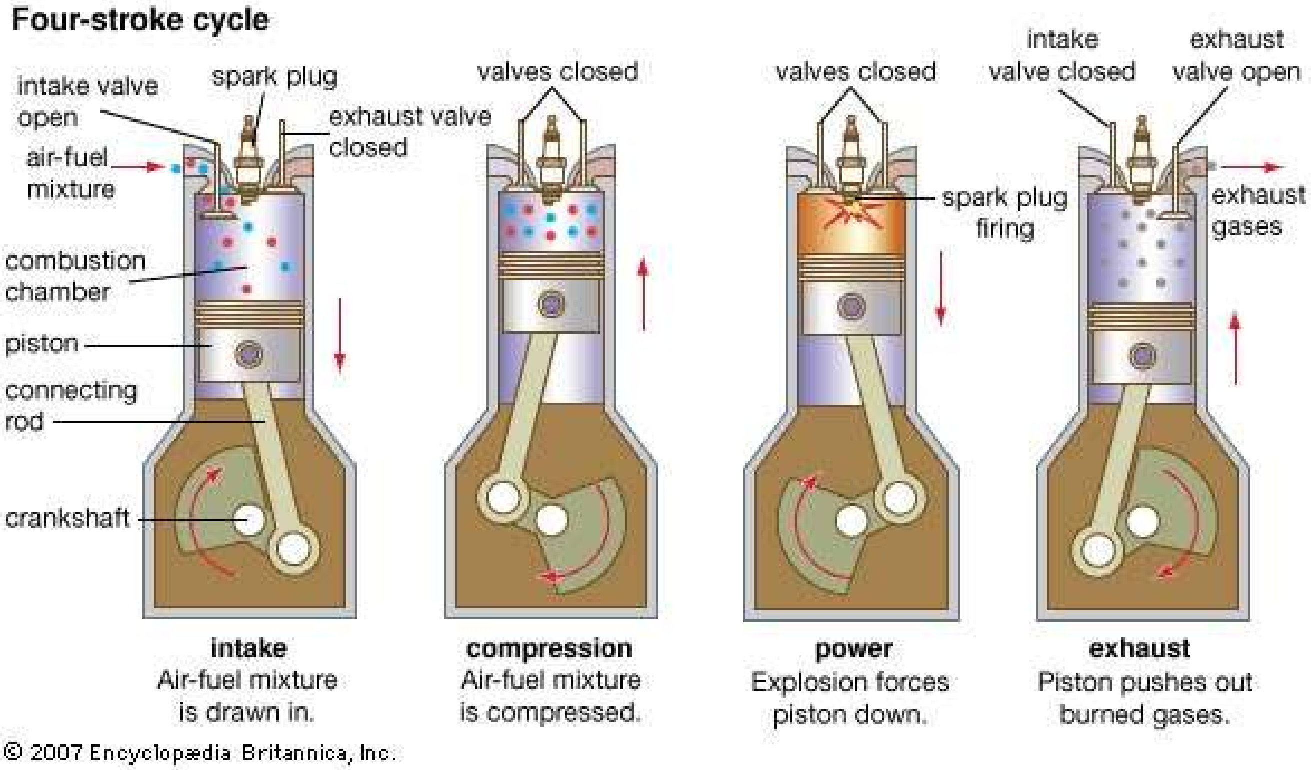
$$r = \frac{V_{max}}{V_{min}} = \frac{V_{BDC}}{V_{TDC}}$$

$$W_{net} = \text{MEP} \times \text{Piston area} \times \text{Stroke} = \text{MEP} \times \text{Displacement volume}$$

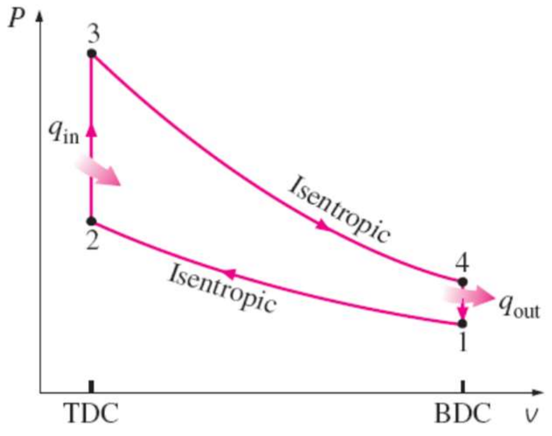
Mean effective pressure

$$\text{MEP} = \frac{W_{net}}{V_{max} - V_{min}} = \frac{w_{net}}{v_{max} - v_{min}} \qquad (\text{kPa})$$

Working Principle of Reciprocating Engine



Source: https://www.britannica.com/technology/four-stroke-cycle



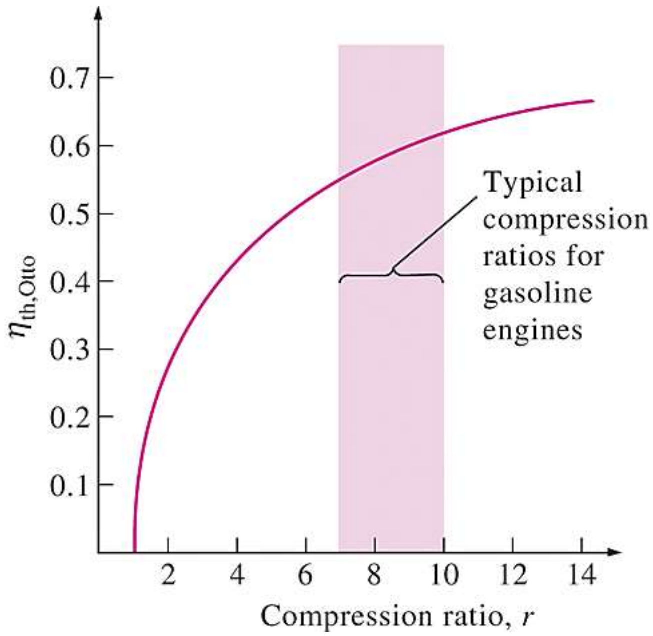
$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = \Delta u \qquad \text{(kJ/kg)}$$

$$q_{in} = u_3 - u_2 = c_v(T_3 - T_2)$$

$$q_{out} = u_4 - u_1 = c_v(T_4 - T_1)$$

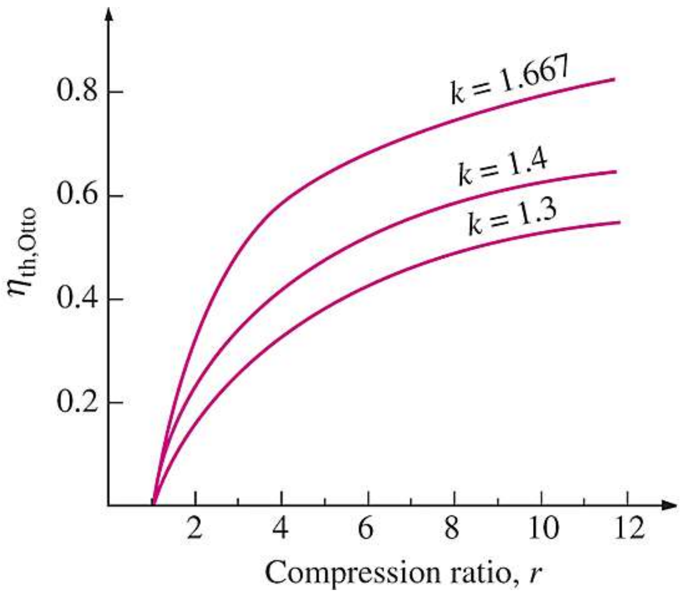
$$\eta_{th,Otto} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_4 - T_1}{T_3 - T_2} = 1 - \frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)}$$

$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{k-1} = \left(\frac{v_3}{v_4}\right)^{k-1} = \frac{T_4}{T_3} \qquad r = \frac{V_{max}}{V_{min}} = \frac{V_1}{V_2} = \frac{v_1}{v_2}$$



$$\boxed{\eta_{th,Otto} = 1 - \frac{1}{r^{k-1}}}$$

In SI engines, the compression ratio is limited by autoignition or engine knock.

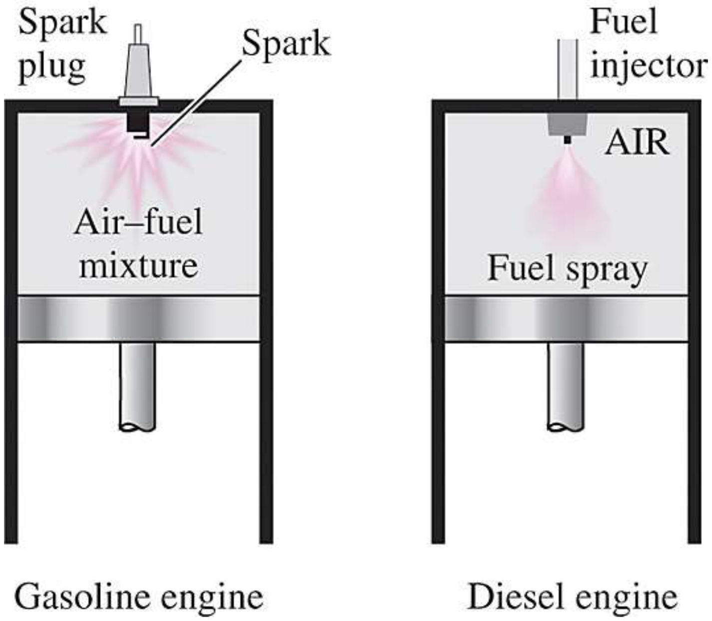


The thermal efficiency of the Otto cycle increases with the specific heat ratio *k* of the working fluid (in this case k=1.4, air at room temp.).

Thermal efficiency of the ideal Otto cycle as a function of compression ratio.

Diesel Cycle

In diesel engines, only air is compressed during the compression stroke, eliminating the possibility of autoignition (engine knock). Therefore, diesel engines can be designed to operate at much higher compression ratios than SI engines, typically between 12 and 24.



- 1-2 isentropic compression
- 2-3 constant-pressure heat addition
- 3-4 isentropic expansion
- 4-1 constant-volume heat rejection.

In diesel engines, the spark plug is replaced by a fuel injector, and only air is compressed during the compression process.

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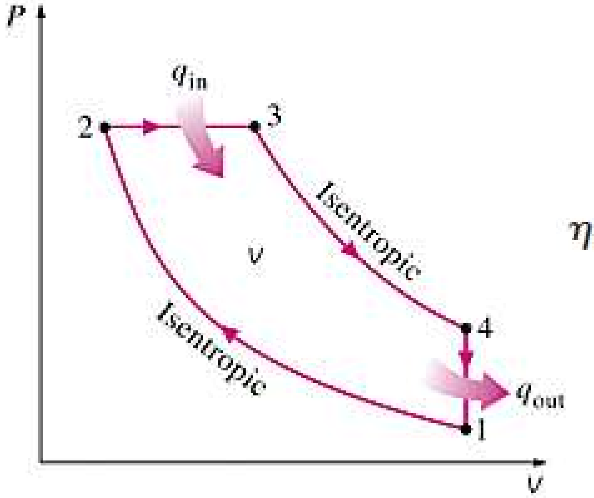
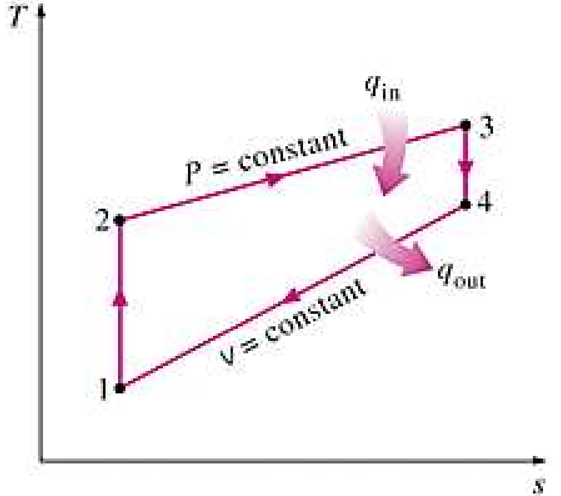


(a) P- v diagram



(b) T-s diagram

$$q_{in} = P_2(v_3 - v_2) + (u_3 - u_2)$$
$$= h_3 - h_2 = c_p(T_3 - T_2)$$

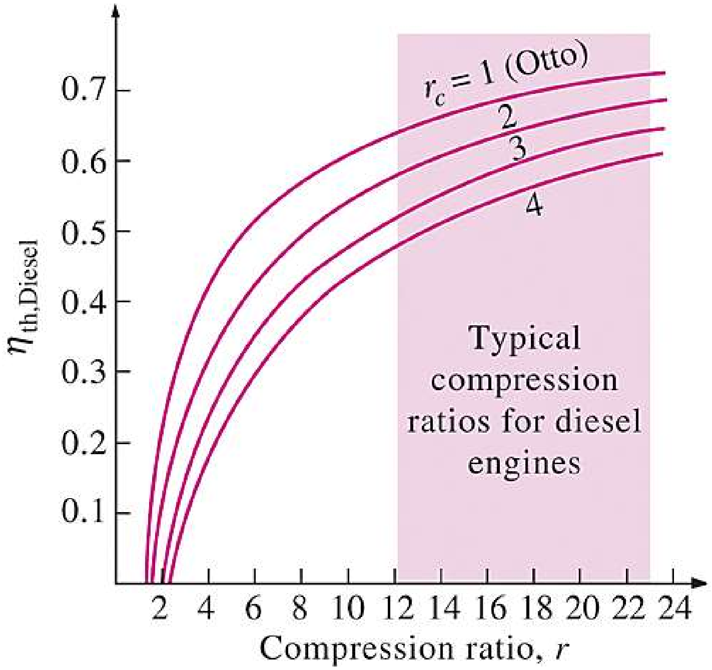
$$-q_{out} = u_1 - u_4 \rightarrow q_{out} = u_4 - u_1 = c_v(T_4 - T_1)$$

$$\eta_{th,Diesel} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_4 - T_1}{k(T_3 - T_2)} = 1 - \frac{T_1(T_4/T_1 - 1)}{kT_2(T_3/T_2 - 1)}$$

$$r_c = \frac{V_3}{V_2} = \frac{v_3}{v_2}$$ Cutoff ratio

$$\eta_{th,Diesel} = 1 - \frac{1}{r^{k-1}}\left[\frac{r_c^k - 1}{k(r_c - 1)}\right]$$

$\boxed{\eta_{th,Otto} > \eta_{th,Diesel}}$ for the same compression ratio

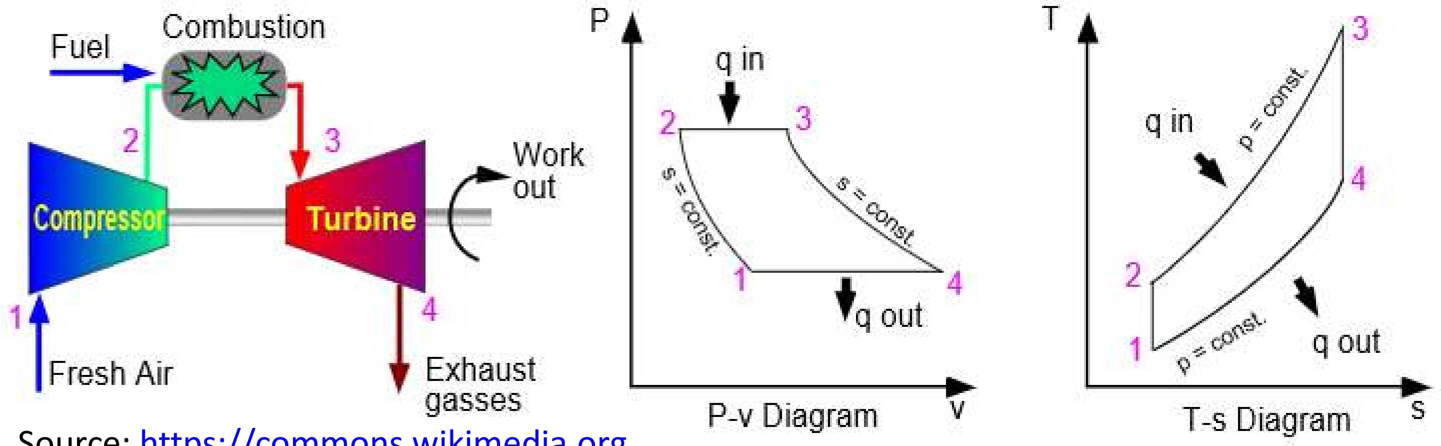


Thermal efficiency of the ideal Diesel cycle as a function of compression and cutoff ratios (k=1.4).

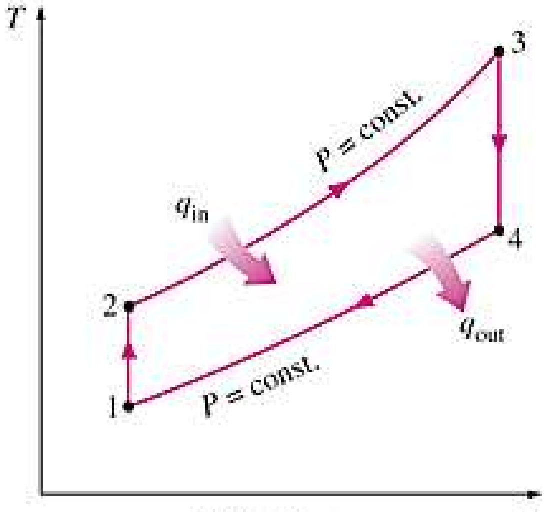
Brayton Cycle: The Ideal Cycle for Gas-Turbine Engines

The combustion process is replaced by a constant-pressure heat-addition process from an external source, and the exhaust process is replaced by a constant-pressure heat-rejection process to the ambient air.

1-2 Isentropic compression (in a compressor)
2-3 Constant-pressure heat addition
3-4 Isentropic expansion (in a turbine)
4-1 Constant-pressure heat rejection



Source: https://commons.wikimedia.org



(a) T-s diagram

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_{exit} - h_{inlet}$$

$$q_{in} = h_3 - h_2 = c_p(T_3 - T_2)$$

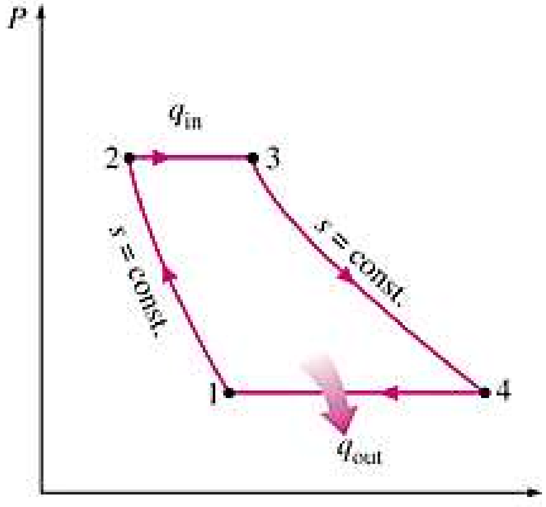
$$q_{out} = h_4 - h_1 = c_p(T_4 - T_1)$$

$$\eta_{th,Brayton} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{c_p(T_4 - T_1)}{c_p(T_3 - T_2)} = 1 - \frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = \left(\frac{P_3}{P_4}\right)^{(k-1)/k} = \frac{T_3}{T_4} \qquad r_p = \frac{P_2}{P_1}$$

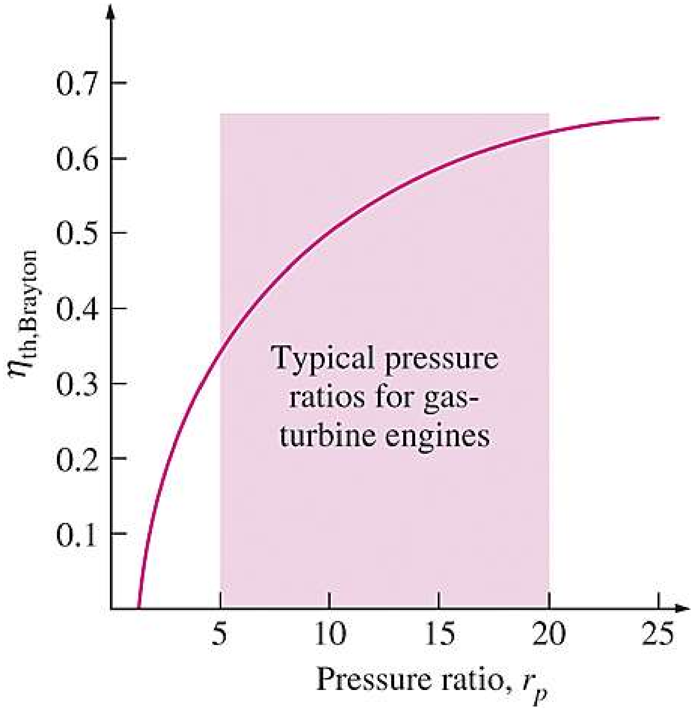
Pressure ratio

$$\eta_{th,Brayton} = 1 - \frac{1}{r_p^{(k-1)/k}}$$



(b) P-v diagram

T-s and *P-v* diagrams for the ideal Brayton cycle.



Thermal efficiency of the ideal Brayton cycle as a function of the pressure ratio.

Conclusion

- Generally, gas power cycle analysis utilize air standard assumption and the cycle considered as ideal cycle.
- Otto cycle applied on the gasoline engine which utilizing compression ratio up to 12.

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Author Information:

Mr. Mohd Yusof Taib
Faculty of Mechanical Engineering
Universiti Malaysia Pahang
26600 Pekan, Pahang
Malaysia

myusof@ump.edu.my